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COLLISIONLESS SHOCK WAVES

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THE THICKNESS OF THE INTERPLANETARY COLLISIONLESS SHOCK WAVES

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ABSTRACT

The thicknesses of magnetic structures of the interplanetary shock waves related to the upstream solar wind plasma parameters are studied. From this study the following results have been obtained: the measured shock thickness increases for decreasing upstream proton number density and decreases for increasing proton flux energy. The shock thickness strongly depends on the ion plasma β , i.e. for higher values of β the thickness decreases. It has been established that the interplanetary shock thickness depends on the Alfvén Mach number taken in the direction of the normal, M_{An} : the shock wave becomes thicker with increasing M_{An} .

АННОТАЦИЯ

Изучена толщина магнитных структур связанных с межпланетными ударными волнами и их связь с параметрами солнечного ветра. Получены следующие результаты: измеренная толщина ударной волны растет с уменьшением плотности протонов, а с возрастанием энергетического потока протонов уменьшается. Толщина ударной волны сильно зависит от β ионной плазмы: при больших значениях β толщина уменьшается. Установлено, что толщина межпланетной ударной волны зависит также от числа M_{An} Алфвена Маха измеренного в направлении нормали, с увеличением M_{An} ударная волна становится шире.

KIVONAT

A bolygóközi lökéshullámokkal kapcsolatos mágneses strukturák vastagságát vizsgáljuk a napszél paraméterekkel összefüggésben. A következő eredményeket kaptuk: a mért lökéshullám vastagság növekszik a csökkenő protonszűrűséggel, a protonok energiafluxusának növekedtével pedig csökken. A lökéshullám vastagsága erősen függ az ion plazma β értékétől: β magasabb értékeinél a vastagság csökken. Megállapítottuk, hogy a bolygóközi lökéshullám vastagsága a normális irányában mért M_{An} Alfvén Mach számtól is függ, a lökéshullám M_{An} növekedésével szélesebbé válik.

INTRODUCTION

In the last few years, the collisionless shock waves in the space and laboratory plasmas have become a topic of intense study and interest. This interest stems partly from observation of the earth's bow shock and from observation of the flare-generated interplanetary shocks for plasma heating in thermonuclear fusion experiments.

Numerous laboratory experiments are there at present to increase the understanding of interplanetary space phenomena.

In this paper we wish to present new experimental results developed for the study of the fine structure of collisionless shock waves in the interplanetary space which is still one of the most interesting problems of plasma physics. It would be of great significance to understand how the shock thickness depends on the measured interplanetary upstream plasma parameters $/n_1, B_1, T_{el}, T_{il}, \theta_{nB}^{\wedge}, \dots$, etc./ and on a number of important dimensionless plasma parameters $/\beta, M_a, T_e / T_i, \dots$, etc./.

The term "collisionless shock wave" itself implies some collective process which dominates binary collisions in producing a plasma transition layer which may be characterized by a single parameter, the shock thickness L_s /Krall, 1979/. In many cases, the collective process is highly ordered: rapid compression of a plasma results in the formation of a large amplitude steepening wave. The thickness of this steepening can be limited either by the dispersive nature of the wave or by dissipation in the large gradients developed /Paul, 1969/. If the plasma wave steepens to a thickness limited by the dispersive properties of the wave, producing a laminar shock structure of width L_s . In other case the collective process is turbulent. The transition from a laminar to a turbulent shock structure is conveniently described by the development of an instability /Sagdeev, 1966/. Instabilities are usually classified as macroscopic or microscopic. The instabilities, generated by the multiple ions streams, or by anisotropic pressure, will often provide enough dissipation to maintain a steady state transition layer of thickness determined by the characteristics of the instabilities.

The evolution of the shock thickness is relatively simple in the case of the laminar structure; in the case of the turbulent structure, however, a quantitative analysis is extremely complicated. Nevertheless, the mechanisms which are important in this case are already qualitatively clear.

The thickness of the turbulent collisionless shock wave front is determined by the condition that the directed energy should be dissipated across the wave front. Knowing the thickness of the wave front it is possible to calculate the effective resistivity which is necessary for this dissipation and is proportional to the thickness of the wave front and its velocity:

$$\eta^+ \approx L_s V_s.$$

Because of the infrequent occurrence of interplanetary shocks and practical absence, until recently, of suitable high-time resolution instrumentation of interplanetary spacecrafts, the study of the thickness of the interplanetary shock waves is in a relatively early stage of investigation. Estimation of the thickness of flare-generated interplanetary shock waves, using high-time resolution spacecraft magnetic field data, have been reported by Dryer et al./1975/, Intriligator /1977/, Smith et al./1977/, Fairfield/1974/, Russell and Greenstadt/1979/, Neubauer et al./1977/ and Gurnett et al./1979/. On the other hand, on the basis of a limited number of events which are currently available for analysis, we have attempted to determine which initial plasma parameters control the variations of the interplanetary shock wave thickness.

Measurements of interplanetary shock waves

In most interplanetary space experiments the solar wind plasma parameters /V- solar wind bulk velocity; n-proton density; T_p -proton temperature/ and the interplanetary magnetic field magnitude /B/ are reasonably well known. However, reliable measurements of electron temperature are available in only a few cases.

If a large concentration of energy in a solar flare is suddenly released, it will spread into the surrounding corona and interplanetary space and at its forefront a shock wave will be formed. An interplanetary shock wave is an abrupt but continuous change in the state of the solar wind plasma. The present study considers 12 interplanetary shocks observed with various spacecrafts. The upstream interplanetary plasma and magnetic field data for these shock waves are listed in Table I.

The interplanetary shock wave observed on March 30, 1976 by both Max-Planck-Institute plasma analyzer on Helios-2 and TU Braunschweig search-coil and flux-gate magnetometer/Gurnett et al., 1979/ serves as a typical example of the interplanetary measurements. Figure 1. shows the solar wind plasma and magnetic field properties measured on the Helios-2 spacecraft; the abrupt jumps in proton and electron temperature, proton density, solar wind speed and magnitude of the interplanetary magnetic field at 1744 UT indicate the passage of the IP shock.

Table I

Date	Shock Time UT	n_p (cm^{-3})	V (km/s)	T_p (10^5K)	B (nT)	V_s (km/s)	θ_{nB} (deg)	Spacecraft
Aug. 11, 1967	0554	6.0	431	1.60	7.7	504	~90	Exp.34
Aug. 29, 1967	1732	2.6	418	0.65	5.5	402	70	Exp.34
Apr. 05, 1968	1326	18.0	326	0.96	9.1	380		OGO-5
Feb. 02, 1969	0600	7.3	379	0.76	8.1	449	83	Pioneer-9
Apr. 21, 1971	1622	9.1	346	0.34	8.0	475	~90	Exp.43
May. 17, 1971	0625	25.0	363	0.92	~8.0	510	81	Exp.43
May. 30, 1971	0733	14.5	334	0.75	8.0	470	~90	Exp.43
Aug. 04, 1972	2323	0.7	685	0.20	9.0	1183	64	Pioneer-9
Aug. 06, 1972	1518	1.6	412	0.50	2.5	717	~	Pioneer-10
Jan. 06, 1975	2044	6.0	580	1.50	7.3	625	83	Helios-1
Mar. 30, 1976	1744	5.6	419	0.15	43.4	806	48	Helios-2
Oct. 26, 1977	2327	20.0	290	1.50	8.5	472	63	ISEE-1

The inertial shock speed:

If the plasma density or magnitude of interplanetary magnetic field and flow velocity are known on both sides of the a shock, the equation of mass continuity can be used to compute the inertial speed V_s of the shock front. A series of calculations have been carried out to estimate the local /inertial/ speed of the shock front /Intriligator, 1977/. These calculations are based on the assumption that the shocks are quasi-perpendicular, since they are associated with significant changes in the magnetic field magnitude with little change in direction. Then the conservation of magnetic flux leads to the relation for the inertial speed of the shock:

$$V_s < V, B > = (V_2 B_2 - V_1 B_1) / (B_2 - B_1) \quad /1/$$

where V_1 and V_2 are the values of the solar wind velocity before and after the shock, respectively; B_1 and B_2 are the values of the magnetic field magnitude before and after the shock, respectively.

The shock speed is remarkably similar to those, calculated using equation /1/, when the shock speed is calculated by using the equation:

$$V_s < V, n > = (V_2 n_2 - V_1 n_1) / (n_2 - n_1) \quad /2/$$

where n_1 and n_2 are the solar wind proton number density before and after the shock, respectively. Michalov et al./1974/ calculated the shock speed using the equation:

$$V_s = [(V_2 n_2 - V_1 n_1) / (n_2 - n_1)] \hat{n} \quad /3/$$

where \hat{n} , is the best fit for the shock normal. Chao and Lepping /1974/ calculated the local shock speed from multiple spacecraft observation of the shock front. The results from estimating the local shock speed by using these equations are shown in Table I.

Shock geometry:

It is very important for the study of the shock thickness to describe the geometrical situation of the shock front. There are two main classes of magnetic shocks, by which we mean those in which the flowing plasma includes a magnetic field. These classes are the perpendicular and oblique ones. The perpendicular one is actually a narrowly-defined case in which the angle $\theta_{\hat{n}B}$ of the magnetic field relative to the shock normal is almost exactly 90° . More precisely, the restriction on this class is that the complement of $\theta_{\hat{n}B} \leq \arctan (m_e/m_p)^{1/2}$ which means that B must be within 1.3° of tangency to the shock "surface". The division oblique, is intended to include every other $\theta_{\hat{n}B}$. Theoretically, a collisionless shock wave would be considered to be oblique if the class of $\theta_{\hat{n}B}$ from 90° were greater than $(m_e/m_p)^{1/2}$ rad, i.e. $\geq 1.3^\circ$. This classification for study of interplanetary shock waves is not complete. Greenstandt/1974/ introduced a revised classification and used two additional experimental divisions quasi-perpendicular and quasi-parallel. The quasi-perpendicular division numerically means that $50^\circ \leq \theta_{\hat{n}B} \leq 88^\circ$. The derived quantities are given in Table I. In the $\theta_{\hat{n}B}$ column, the table shows that at the shock of 30 March 1976 $\theta_{\hat{n}B}$ is 2.0° away from the quasi-perpendicular orientation, whereas at other shocks, it was quasi-perpendicular.

Shock thickness:

Although there are several length scales associated with interplanetary shock waves, the magnetic structure affords the most easily measured shock thickness L_s . The high resolution magnetic field data measured by various spacecrafts were used to infer shock thickness at heliocentric distance near 1 AU: Fig. 2 shows the examples of forward shocks at high-time resolution measurements of the magnetic field strength on Pioneer 10 for 120 seconds around the passage of shocks /Smith and Wolfe, 1977/. Field strength is in gammas $/1\gamma = 1nT/$. The time resolution is typically a fraction of one second. Each shock involves a large jump in field magnitude. These measurements reveal either irregular or quasi-periodical structures. In this figures, the measured B/t gives a clear indication of the transit time/rise time/ τ_s for the shock passing Pioneer and the knowledge of the shock speed V_s permits to easily compute the magnetic shocks thickness $L_s = \tau_s V_s$. The quantity L_s can be taken as the effective thickness of the shock front which connects the two plasma states: the unperturbed upstream state, /before the passage of the shock wave/ and the perturbed state /after the passage of the shock/.

The measurements of interplanetary shocks thickness L_s are listed in Table II. where τ_s is the shock rise time as deduced from the magnetic field data, and V_s is the shock inertial speed. The shock thickness varied from 40 km to 12×10^4 km. These shock thickness can be compared with the independent calculation of the proton inertial length c/ω_{pi} where ω_{pi} is the upstream ion plasma frequency $(4\pi ne^2/m_i)^{1/2}$. The next column at Table II give the ratio of L_s to c/ω_{pi} . There is general correspondence between c/ω_{pi} and the shock thickness with the smallest c/ω_{pi} to the smallest L_s and the largest c/ω_{pi} corresponding to the largest L_s . The shock thickness varied from $440 c/\omega_{pi}$ to $0.9 c/\omega_{pi}$ /see Table II/. All the theoretical mechanisms known at present predict a thickness of the collisionless shock transition layer in a plasma of the order of the ion Larmor radius. The thickness of shock measured in laboratory agrees with those predicted by theory /Paul,1970/. In the cases of the earth's bow shock the measured thickness is also of the order of c/ω_{pi} or less /Holzer et al. 1972/.

Table II.

Data	Shock Time UT	τ_s (sec)	V_s (km/s)	L_s (km)	β_i	M_A	c/ω_{pi}	$L_s/c/\omega_{pi}$ (km)
Aug. 11, 1967	0554	2.00	504	1000	0.56	1.07	92.6	10.8
Aug. 29, 1967	1732	5.00	492	2460	0.19	1.00	140.7	17.5
Apr. 05, 1968	1326	0.27	380	102	0.72	1.20	53.5	1.9
Feb. 02, 1969	0600	3.00	449	1340	0.29	3.70	84.0	15.9
Apr. 21, 1971	1662	3.00	475	1425	0.17	1.37	75.2	18.9
May. 17, 1971	0625	0.08	510	40	1.35	2.72	45.4	0.9
May. 30, 1971	0733	0.36	470	169	0.59	2.98	59.6	2.8
Aug. 04, 1972	2323	101.00	1183	12×10^4	0.016	2.90	271.3	442.3
Aug. 06, 1972	1518	2.00	717	1434	0.27	7.00	179.4	7.9
Jan. 06, 1975	2044	0.25	625	160	0.59	0.7	92.3	1.7
Mar. 30, 1976	1744	0.07	627	44	0.016	1.07	95.9	0.6
Oct. 26, 1977	2327	0.19	472	90	1.44	3.00	50.9	1.8

The fine structure of an interplanetary shock wave and its thickness have been studied by Russell and Greenstadt/1979/ for the case of 26 October, 1977 presented in Figure 3. This figure shows a 20 second duration of interplanetary magnetic field records from spacecrafts ISEE-1 and ISEE-2 surrounding the interplanetary shock. The shock caused an increase in the interplanetary magnetic field from 8 nT to 15.3 nT. ISEE-1 was transmitting data at its highest rate so that the magnetometer was providing 16 samples per second. However, ISEE-2 was providing only 4 samples per second. The

upstream wave train is clearly seen in the ISEE-1 records. The separation of the two spacecrafts was 307 km along the shock normal and 399 km projected into the shock plane, the 0.65 sec separation in time implies a shock velocity of 472 km/sec. Using the rise of the field magnitude from minimum to maximum Russell and Greenstadt/1979/ obtain a shock thickness of 90 km. Using the preliminary solar wind parameters for the upstream region they obtain for c/ω_{pe} : 1.2 km and for c/ω_{pi} : 50 km. Thus the magnetic shock thickness was close to twice the ion inertial length.

Dryer et al./1975/ also infer the upper limits of the shock thickness for 5 shocks. The estimated upper limits of all of the shock thicknesses are higher than 2-5 ion inertial lengths. Fairfield/1974/ studied three interplanetary shock waves, which also indicated that ion inertial length is smaller than the thickness of magnetic shock, Smith and Wolfe /1978/ used the high resolution magnetic field data to infer the shock thickness at large heliocentric distances.

The typical transit time of the shocks passed by Pioneer 10 or 11 is approximately 2 sec. Using an average velocity of propagation of 453 km/sec one can infer a typical thickness of 10^3 km at heliocentric distances 2-4 AU. Using the local shock speeds and the high-time resolution magnetic field data, Intriligator /1977/ estimated the thickness for August 6.1972, 1520 UT forward shock observed at Pioneer 10. For this shock, using $V_s = 717$ km/sec and $\tau_s \sim 2$ sec, she obtained $L_s = 1400-1500$ km. This thickness obtained by Intriligator is substantially less than upper limit $/L_s \sim 11.6 \times 10^4 \text{ km}/$ for some shocks observed at 0.78 AU with Pioneer 9 as reported by Dryer et al./1976/.

Variation of shock thickness with measured and computed plasma parameters

The collisionless shocks thickness probably depends on a large number of important measured and calculated dimensionless upstream /pre-shock/ plasma parameters. Let us start by summarising those parameters which are more significant:

$$L_s = c/\omega_{pi} F[(n, B, \theta_{\hat{n}B}, T_e, T_p), (T_e/T_p, \beta, \alpha, M_A, V_A, m_i/m_e)] \quad /4/$$

Where: n - is the upstream /pre-shock/ proton number density $/\text{cm}^{-3}/$

B - is the upstream magnetic field magnitude $/nT/$

T_e and T_p - are upstream electron and proton temperatures

$\theta_{\hat{n}B}$ - is the angle between the shock normal and the magnetic field vector in front of the shock

T_e/T_p - is the ratio of electron and ion temperatures

A great variety of shock wave types has been proposed /Formisano, 1974/ the structure and thickness of which depend on the parameters α, β, M_A, V_A and others.

β - the ratio of plasma pressure over magnetic field pressure:

$$\beta = 8\pi n k T_p / B^2 \quad /5/$$

α -the ratio of flow kinetic and magnetic energy density:

$$\alpha = 4\pi n_p m_p v_s^2 / B^2 \quad /6/$$

Dynamical parameter: Alfvén Mach number

$$M_A = U_s / V_A \quad /7/$$

where $U_s = V_s - V$; V_s -is local shock velocity; V -is pre-shock solar wind velocity; V_A -is Alfvén velocity

$$V_A = B / (4\pi n_p m_p)^{1/2} \quad /8/$$

A considerable fraction of the these parameters $[\beta, \theta, n_B, M_A, T_e/T_p]$ and their association with collisionless shock thickness were experimentally investigated in the laboratory plasma [Alikhanov et al., 1968; Hintz, 1968]. The variation of interplanetary shock wave thickness L_s parameters such as $n_p, B, M_A, V_A, \beta, \alpha$, etc. has not been studied yet. It would be of great significance to understand how the interplanetary shock thickness depends on the above mentioned plasma parameters.

a./ Variation of shock thickness with density

The variation of the measured interplanetary shock thickness L_s versus the upstream proton number density is shown in *Figure 4*, where shock thickness is plotted against density n_p . The thickness L_s is readily seen to increase for decreasing upstream proton density. Also shown/solid line/ is the best fit of the nonlinear mode $L_s = A n_p^{-\alpha}$ to the data. This gave the result

$$L_s = 2.89 \times 10^4 n_p^{-1.92} \quad /km/ \quad (0.25 \leq n_p \leq 80 \text{ cm}^{-3})$$

where the density n_p is given in cm^{-3} . By comparing the experimental shock thickness in *Fig. 4* with the ion Larmor radius /ion inertial length/ which is the characteristic length, associated with the solar wind plasma, important to shock interaction, it may be seen that the measured shock thickness are higher than the Larmor radius above the density of 30 cm^{-3} . For density below 30 cm^{-3} ion Larmor radius become higher than measured shock thickness. The ion Larmor radius /ion inertial length/ for conditions ahead of the shock is given by

$$R_1 = c / \omega_{p1} = (m_1 c^2 / 4\pi n_p e^2)^{1/2} \quad /9/$$

where m_1 is the proton mass, c is the velocity of light and e is the electron charge. One can see, that R_1 a function of the upstream proton density only.

Since the shock thickness is a function of the solar wind proton density and recent spacecraft measurements of solar wind plasma inward to 0.3 AU and outward to 5.0 AU suggest that the proton density on average decreases as R^{-2} [Rosenbauer et al., 1976], as predicated by Parker, also a similar dependence of shock thickness on heliocentric distance must be found.

In this study we will use a little modified form of the Stelzried's 1970 /equation for the equatorial density radial distribution given by

$$N_{/R/} = 10^8 * \left(\frac{6 \times 10^3}{R^{10}} + \frac{0.003}{R^2} \right) / \text{cm}^{-3} \quad /10/$$

with R in solar radii. In the range of interest for this study $0.3 \leq R \leq 5.0$ AU/ the R^{-10} term is negligible, thus:

$$N_{/R/} = 3 \times 10^5 R^{-2} \quad /11/$$

Then the formula for the interplanetary shock wave thickness variation with heliocentric /radial/ distance is given by

$$L_s = 8.81 \times 10^{-7} R^{3.84} / \text{in km} / \quad /12/$$

where R is in solar radii. The shock wave thickness as a function of density and as a function of heliocentric distance are tabulated in Table III.

Table III

Distance from sun center R (in solar radii)	Heliocentric distance (in A.U.)	Proton density (cm^{-3})	IP Shock thickness (km)
64.1	0.3	72.9	8
85.5	0.4	41.0	23
106.9	0.5	26.2	54
170.9	0.8	10.3	330
213.7	1.0	6.6	779
320.6	1.5	2.9	3.7×10^3
427.2	2.0	1.6	1.1×10^4
598.4	2.8	0.8	4.1×10^4
854.8	4.0	0.4	1.6×10^5
1068.6	4.0	0.3	3.8×10^5

The comparison of these values /also plotted in Fig.4 by crosses/ with measured values of shock thickness and densities demonstrates the validity of the assumptions used in this investigation of the interplanetary shock waves.

Finally, it should be noted that since L_s scales as $n_p^{-1.92}$, the shock thickness for other density can easily be estimated by using Figure 4 or the equation presented above.

In summary, the interplanetary shock thickness are proportional to the upstream proton density and to the quantity c/ω_{pi} .

b. / Shock thickness variation with proton flow energy

Collisionless interplanetary shock thicknesses L_s are shown in *Figure 5a* versus proton flux density /flow energy/ Vn_p . The measured shock thickness, L_s , seen to decrease for increasing proton flow energy. This behaviour argues against the possibility that L_s is determined by the mean free path for ion-ion coulomb interactions, since this mean free path increases with the square of the energy of the incoming ions. The behaviour of L_s with flow energy likewise argues against a shock thickness determined by the ion cyclotron radius. The Larmor radius also proportional to the upstream proton flow energy as shown in *Figure 5b*.

c. / Variation of shock thickness as function of β and α

The influence of the ratio of ion plasma pressure over magnetic field pressure β on the shock thickness has been the subject of several investigations in laboratory experiments /Cairns, 1972; Hintz, 1968/. It was found that the shock thickness L_s strongly depends on the ion pressure, L_s i.e. for higher values of β the thickness increases /Cairns, 1972/.

The variation with β_1 of the thickness of the interplanetary and bow shock waves is investigated in this section of the paper. The variation of L_s with β_1 is shown in *Figure 6* where data marked with crosses /+ / are from Table IV and V and the earth's bow shock data are taken from paper of Morse and Greenstadt /1976/. It is found that the interplanetary and the earth's bow shock waves become thinner with increasing β . These results are in contrast with the relatively large number of experimental and theoretical results from laboratory plasma. On the other hand, our results are principally in agreement with the estimations of Camas et al. /1962/ and Galeev and Karpman /1963/. Camas et al. /1962/ estimated the shock thickness to be

$$L_s \sim 4R_i / \beta M_A \quad /13/$$

Where M_A is the Alfvén Mach number and R_i is the Larmor radius.

The scaling found here is consistent with the results of observation of interplanetary shock waves for $0.01 \leq \beta_1 \leq 1.5$. In fact, these interplanetary shock thicknesses are given within good approximation by

$$L_s = 91.3 \beta_1^{-1.74} \quad /14/$$

Although many of these interplanetary shocks are turbulent, our investigation indicates that the effect of the turbulence on their thickness may be small. On the other hand, it can be seen that the dependence of β_1 and the thickness on the angle θ_{AB} is considerable. For example, the angle between

the magnetic field and the shock normal is $\theta_{\hat{n}B} = 47.5^\circ$, indicating that the interplanetary shock observed on March 30, 1976 was an oblique shock. Since on unusually low upstream density 5.6 cm^{-3} and large upstream field strength were observed at 0.47 AU, the plasma beta is extremely small, $\beta = 0.016$. For this values we would predict a thickness of shock about 10^5 km , while the observed value was only 44 km.

The ratio of flow kinetic to magnetic energy density α is also pertinent. The variation of the shock thickness with α is shown in Figure 7. The shock wave becomes thinner with increasing α .

d./ Variation of shock thickness with Mach numbers

In this analysis we used the Alfvén Mach number $M_A = U_s / V_A$ which relates the relative shock velocity U_s to the upstream Alfvén velocity $[V_A = B(\mu n_p m_p)^{1/2}]$. The relative shock velocity in the solar wind plasma is equal to the difference between the local shock speed, V_s , and the upstream solar wind velocity V_1 . The Alfvén Mach number varied from 0.7 to 7.0 and we found, that the interplanetary shock thickness is independent of M_A , defined in this way.

Dryer et al./1975/ reported on the Pioneer-9 and OGO-5 observations of an interplanetary multiple ensemble on February 2, 1969. At this time, Pioneer-9 was located upstream of earth at an angle $< 2^\circ$ from the earth-sun axis and at a heliocentric radius of 0.87 AU. OGO-5 was located outside the earth's bow shock wave at 1 AU during time period discussed here. The paper of Dryer et al./1975/ presents a comparison of the complete data sets /magnetic field and plasma data/ of both spacecrafts. The shocks wave was analyzed in detail and computed were the following basic parameters; plasma beta ($\beta_{\text{tot}} = 2\mu n_p k (T_p + T_e) / B^2$), total Alfvén Mach number, M_A and Alfvén Mach number in the direction of the shock normal $M_{\hat{n}A}$.

The values of these parameters are listed in Table IV.

Table IV

1969 February, 2 UT	nB deg.	$M_{\hat{n}A}$	M_A	IP Magnetic field		B_2/B_1	β_{tot}
				B_1	B_2		
C1 0600	82.8	16.0	3.7	7	16	2.28	0.2
C5 1030	78.1	6.6	3.1	17	23	1.35	0.4
C6 1104	75.5	5.3	4.8	15	19	1.30	0.3
D5 1944	77.8	7.8	5.2	15	25	1.67	0.3
D6 2000	60.0	2.2	9.0	11	14	1.27	0.6

The C1, C5, C6 and D5 shocks are seen to be supercritical shocks because $M_{A\hat{n}}$ are greater than the classical values /approximately 3/ of the critical Alfvén Mach number usually defined in terms of the components of the vectors along the shock normal direction. On the other hand, the shock D6 is subcritical / $M_{A\hat{n}}=2.2$, i.e. less than ~ 3 /.

The definition of solar ecliptic coordinate system, as well as shock reference planes as used for all results presented in Table IV are shown in Figures 8 and 9 /Dryer et al. 1975/. Figure 8 shows the shock normal upstream interplanetary magnetic field vector, and the relative solar wind velocity vector in the solar-ecliptic system. Here the relative velocity vector is $\vec{V}_{rel} = \vec{V}_{sw} - \vec{V}_s$; \vec{V}_{sw} is the solar wind velocity vector as measured by the essentially inertially-located space probe; \vec{V}_s the shock velocity in the inertial frame of reference. The field $|\vec{B}|$, and velocity vector $|\vec{V}_{rel}|$ are in the upstream IP magnetic field and relative velocity vectors, respectively, with respect to the shock normal in the shock reference system $/x,y,z/$ are shown in Figure 9. Note that θ_B is often referred to as α in collisionless shock theory. Using the coordinate system given in Figure 8 and 9, Dryer et al./1975/ computed the Alfvén Mach number in the direction of the shock normal:

$$M_{A\hat{n}} = V_{\hat{n},rel} / V_{A,\hat{n}} \quad /15/$$

The excellent time resolutions of the magnetometers are used to estimate the shock thickness. Table V shows the shock rise time, the shock velocity in the direction of the shock normal, upper limits for the shock thickness, ion and electron inertial lengths /as computed on the basis of upstream ambient density and magnetic field/.

Table V

Shock	Shock rise time (sec)	Shock velocity (km/s)	Shock thickness (km)	c/ω_{pi} (km)	c/ω_{pe} (km)	$L_s/c/\omega_{pi}$
C1	4.0	449	1800	61	1.4	39.5
C5	1.5	289	430	79	1.8	5.5
C6	1.8	149	270	88	2.1	3.1
D5	1.0	479	480	37	0.9	13.0
D6	0.3	385	100	49	1.1	2.0

Having estimated the shock thickness, now we may compare these with the Alfvén Mach number, $M_{A\hat{n}}$. Figure 10 and Table V show results of this comparison. At low Mach number the rise time the interplanetary magnetic field is very abrupt ~ 0.3 sec or thickness is 100 km/, while at higher Mach numbers it is 1800 km thick /or 4.0 sec the rise time/ i.e., the shock thickness increases with increasing Mach number, calculated in direction of the shock normal. We can see that at the high Mach number $M_{A\hat{n}}=16.0$, the wave front becomes broad $L_s=1800$ km. These results agree with a relatively large number of experimental results from laboratory experiments /Paul, 1970/. It is obvious from Table V that all of the shocks have estimated thicknesses of the order of about 2 to 30 ion inertial lengths.

The next comparison of the interplanetary shock thickness L_s was made with respect to the "critical" or magnetic Mach number M_m which depends on β . The magnetic Mach number is given by

$$M_m = 1 + (3/8) (8\pi n_p k T_p / B^2)^{1/3} = 1 + (3/8) (\beta)^{1/3} \quad /16/$$

The magnetic Mach number M_m varied from 1.08 to 1.42. Figure 11 shows dependence of interplanetary shock thickness on calculated magnetic Mach number M_m . In this magnetic Mach number range, L_s decreases for increasing M_m . This result agrees with the result obtained for laboratory experiment by Yamanaka et al. /1968/.

Summary of results

The interest in the study of interplanetary collisionless shock waves is centred around searching for an empirical relationship between shock thickness and plasma parameters. A brief summary of the results presented here may be stated as follows:

The measured interplanetary shock thickness varies from 40 km to 12×10^4 km, decreasing with higher upstream proton density. The shock thickness is found to vary between 440 and 0.9 times the ion inertial length c/ω_{pi} . Shock thickness L_s is seen to decrease for increasing upstream proton flux (nV).

It was found that L_s strongly depends on the upstream ion pressure, $L_s \sim \beta_i^{-1.74}$.

It has been established that the interplanetary shock thickness is independent of the Alfvén Mach number, but on the other hand it depends on the Alfvén Mach number taken in the direction of the shock normal, $M_{A\hat{n}}$. Shock wave becomes thicker with increasing $M_{A\hat{n}}$.

Finally, the shock thickness tends to decrease with increasing magnetic Mach number M_m .

On the basis of this study, we estimated the interplanetary shock thickness to be

$$L_s = 1.36 c / \omega_{pi} \beta_i^{-1.4} \quad / \text{in km} /$$

Morse and Greenstadt/1976/ have discussed the possibility of calculating the thickness of magnetic structures associated with the earth's bow shock, by using the following expression:

$$L_s = c \Delta B / 4 \pi n e V_e f(T_e/T_i) \quad /17/$$

In this expression, B is the magnetic field magnitude, n is the upstream plasma density, V_e is the electron thermal velocity, e is the magnitude of the electronic charge, T_e and T_i are the electron and ion temperatures, respectively, the function $(T_e/T_i) = V_d/V_e$ was computed by Fried and Gould/1961/. Using this expression we calculated the shock thickness for two extreme events, on August 4, 1972, 2323 UT and on March 30, 1976, 1744 UT. For the August 1972 event we obtained $L_{\text{theor}} = 41 \times 10^4 \text{ km}$ / $L_{\text{measur}} = 12 \times 10^4 \text{ km}$ / and for the March 1976 shock we obtained $L_{\text{theor}} = 61 \text{ km}$ / $L_{\text{measur}} = 44 \text{ km}$ /. We can inspect a good agreement between two quantities.

Recently much effort has been made to understand the origin of the anomalous resistivity β , that arises in the interplanetary collisionless shock waves. Knowing the shock thickness one is able to calculate the resistivity which is proportional to the shock thickness and shock velocity.

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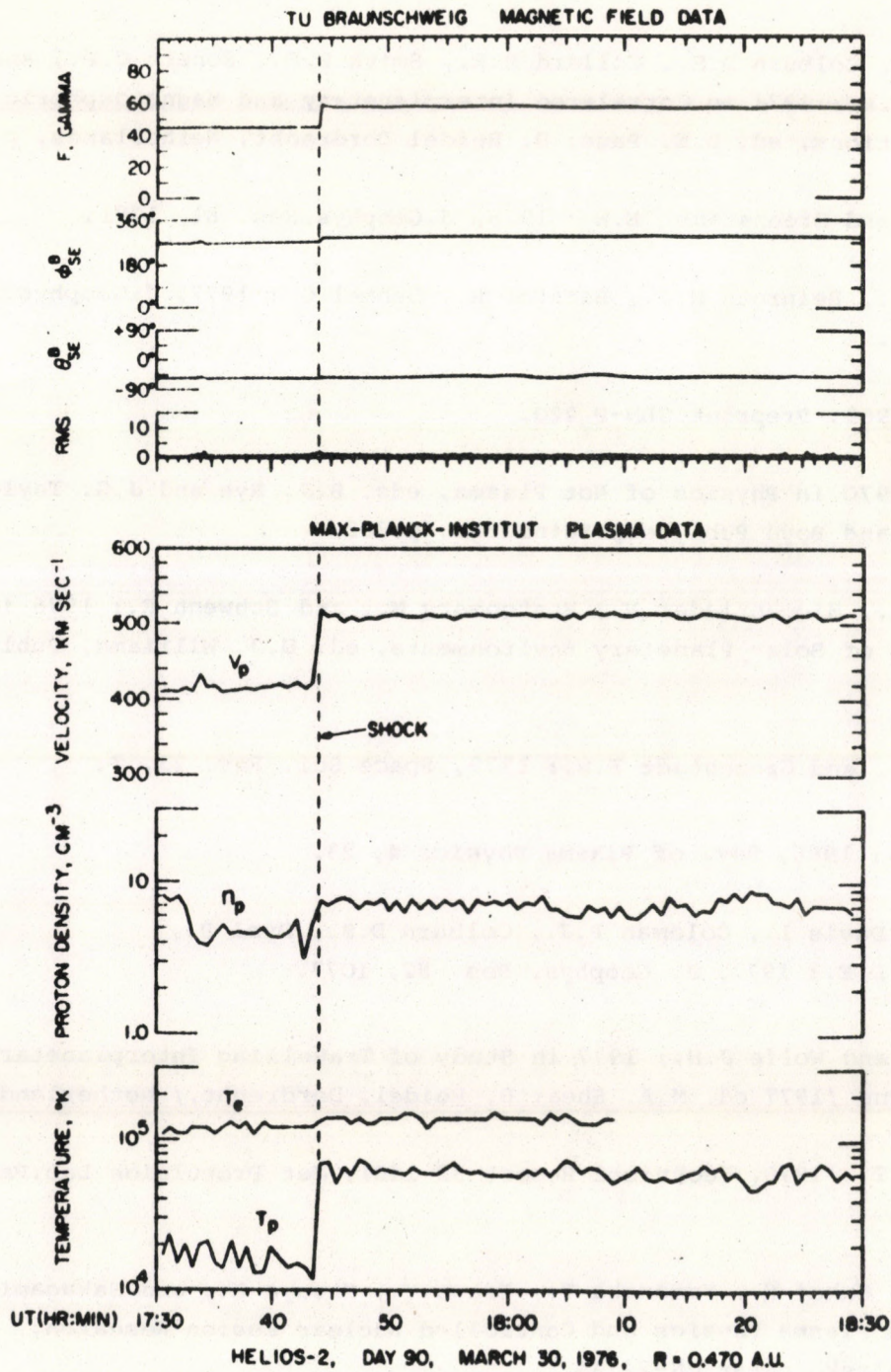


Fig.1. The Helios 2 magnetic field and solar wind plasma data for the interplanetary shock on March 30, 1976 /after Gurnett et al, 1979/.

FORWARD SHOCKS

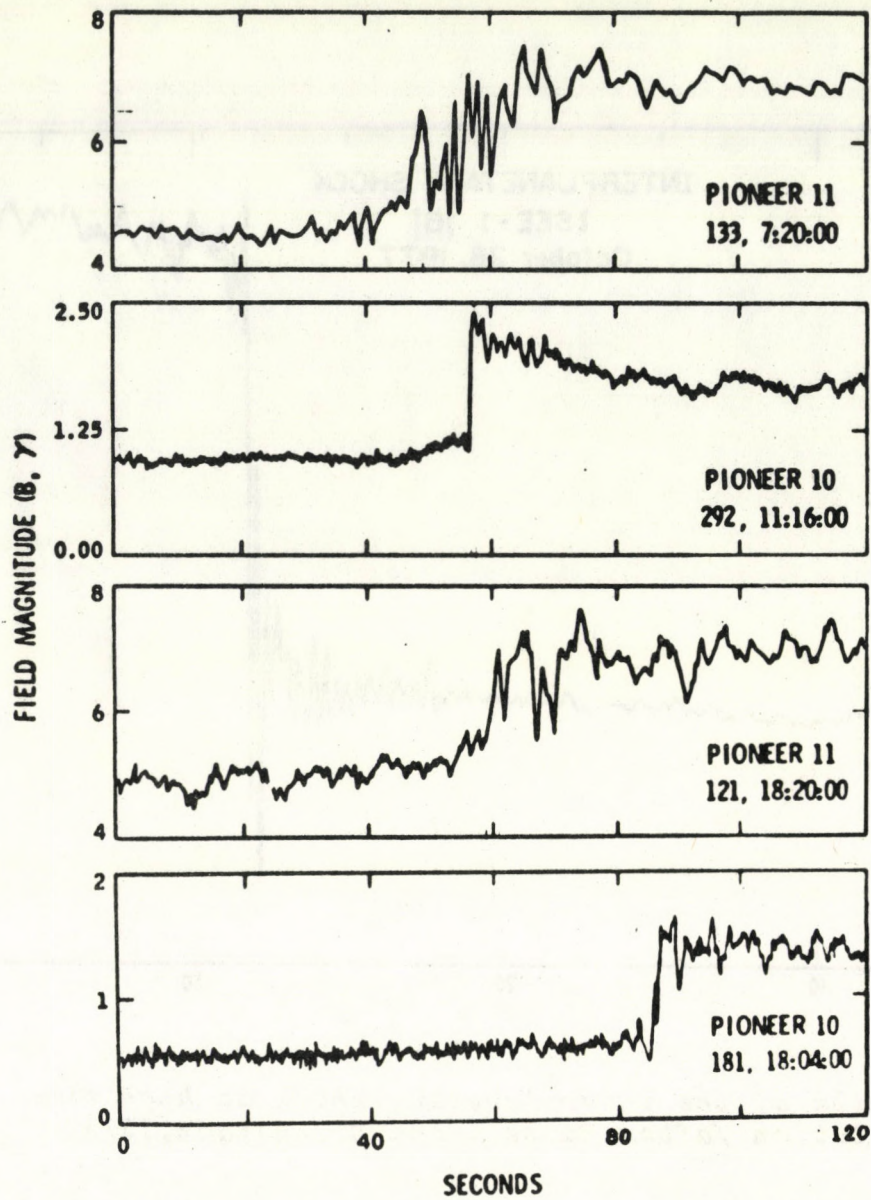


Fig.2. Examples of forward Shocks /after Smith and Wolfe, 1977/.

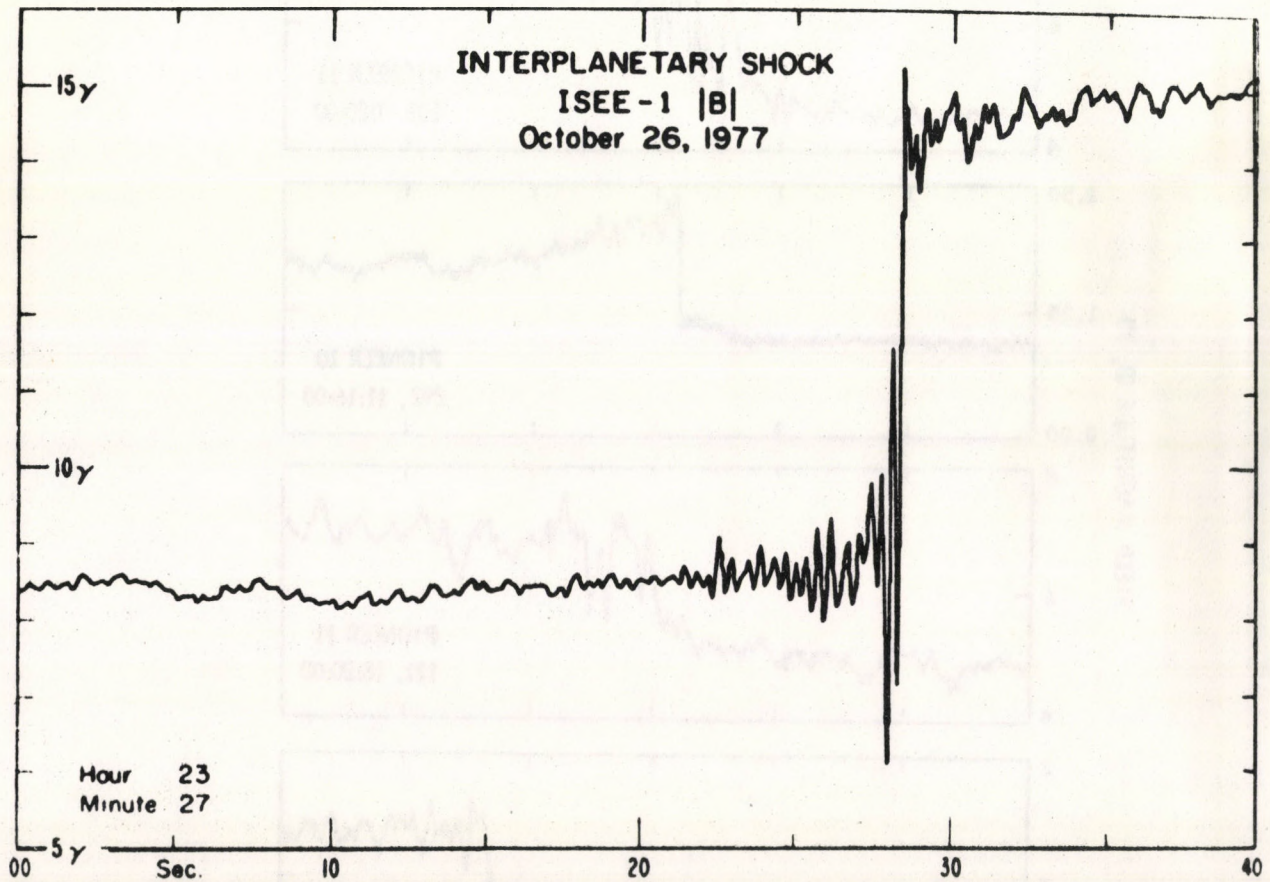


Fig.3. Details of the interplanetary shock at high time resolution /after Russell and Greenstadt, 1979/

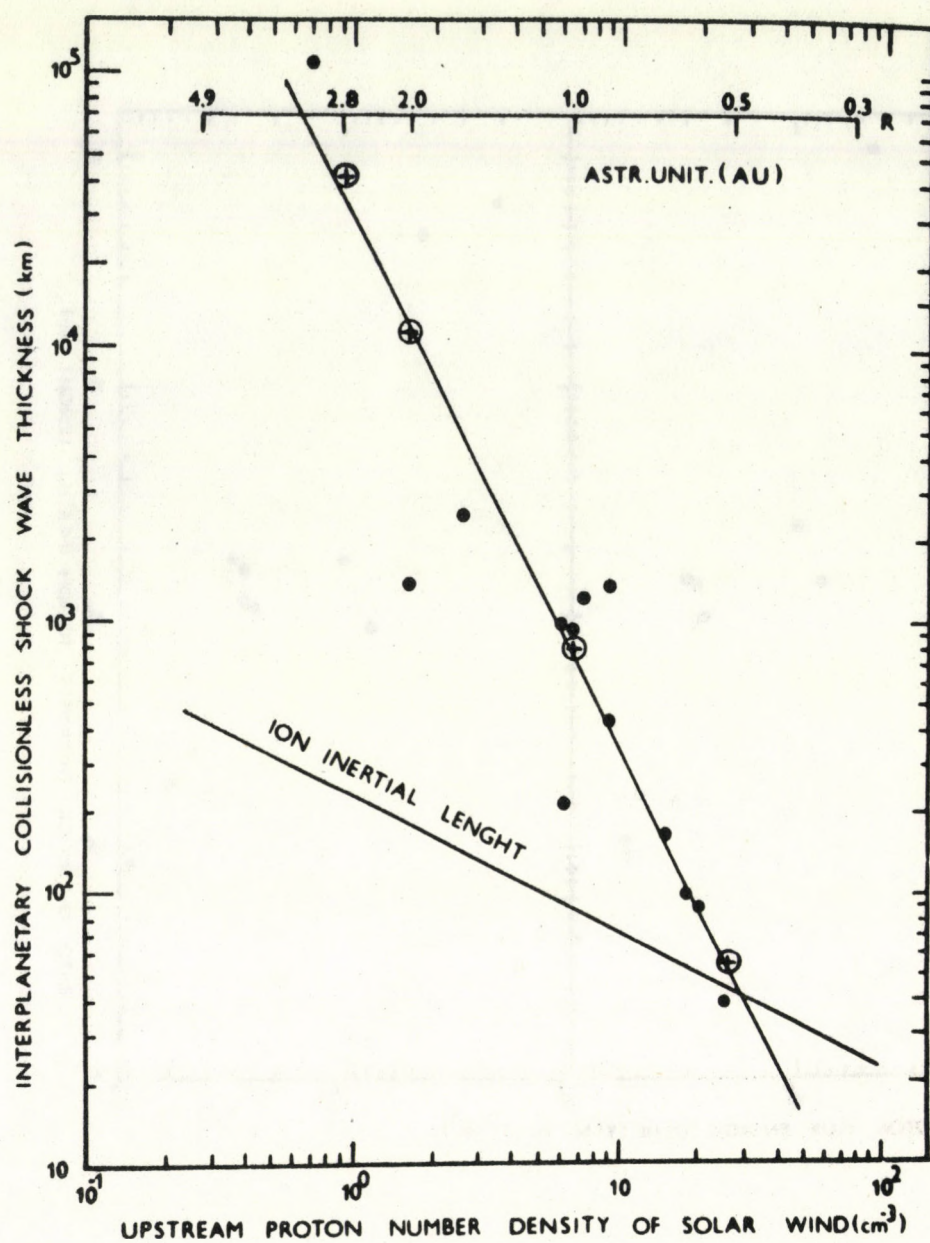


Fig. 4. Interplanetary collisionless shock thickness versus proton number density.

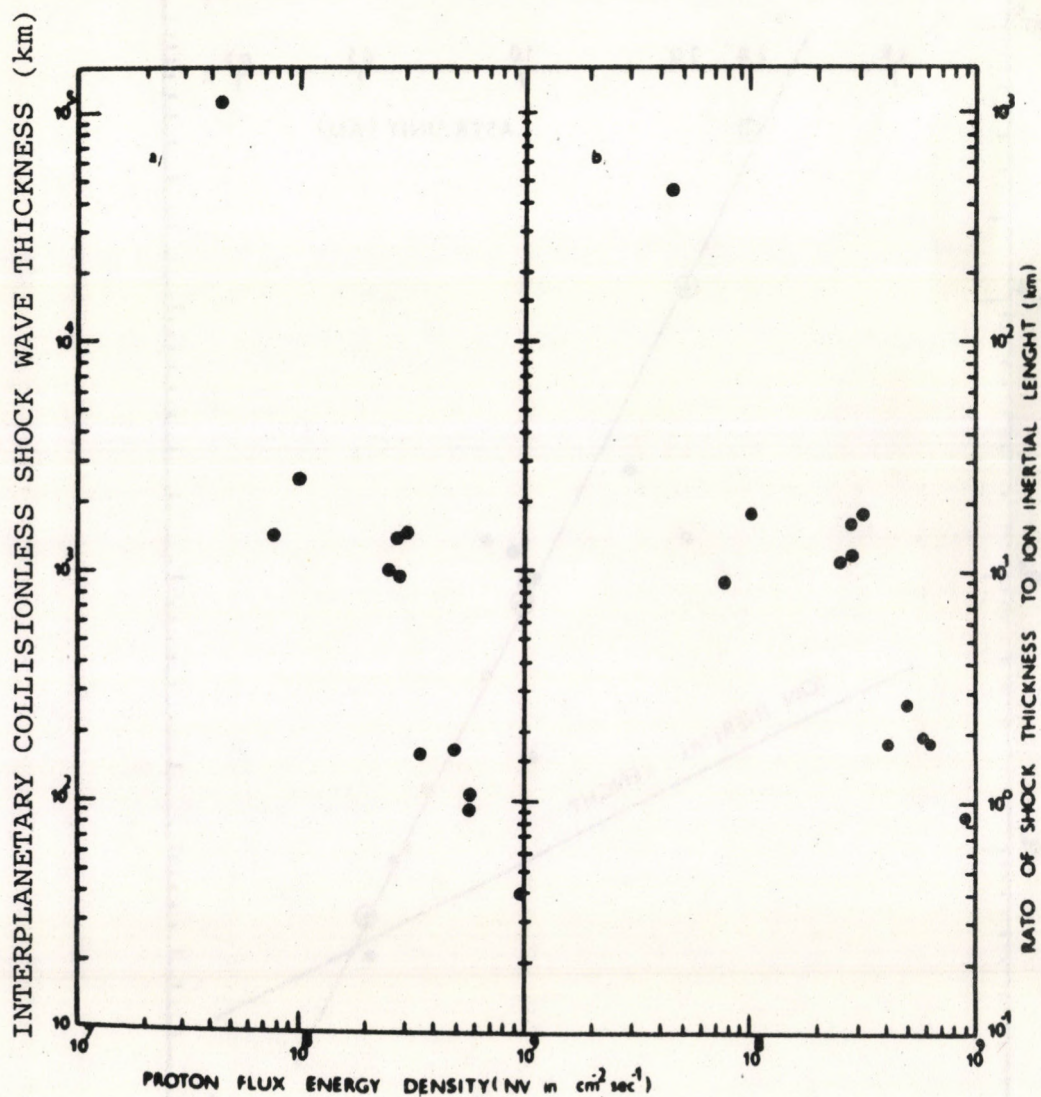


Fig. 5. a. Shock thickness versus proton flux energy density.
b. Ratio of shock thickness to inertial ion length versus proton flux energy density.

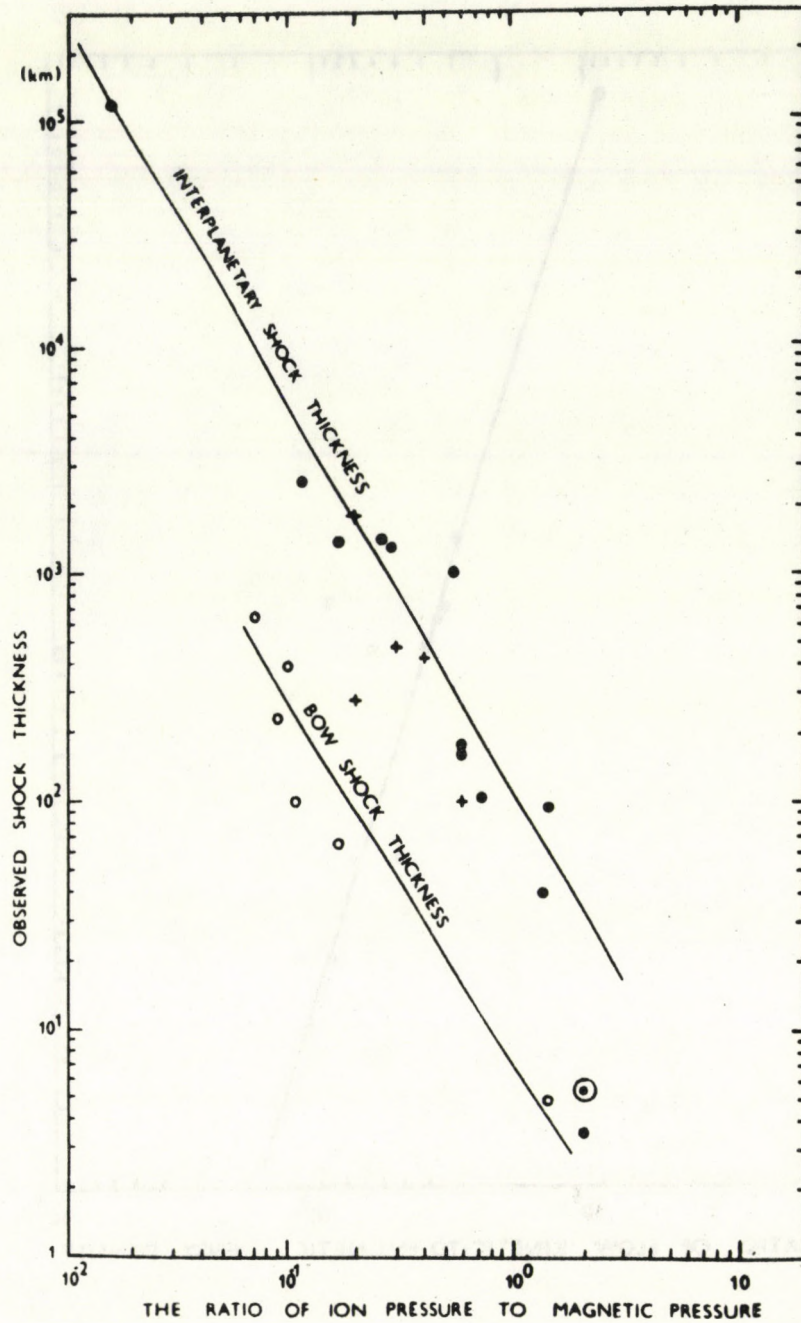


Fig. 6. Shock thickness L_s versus β_i .

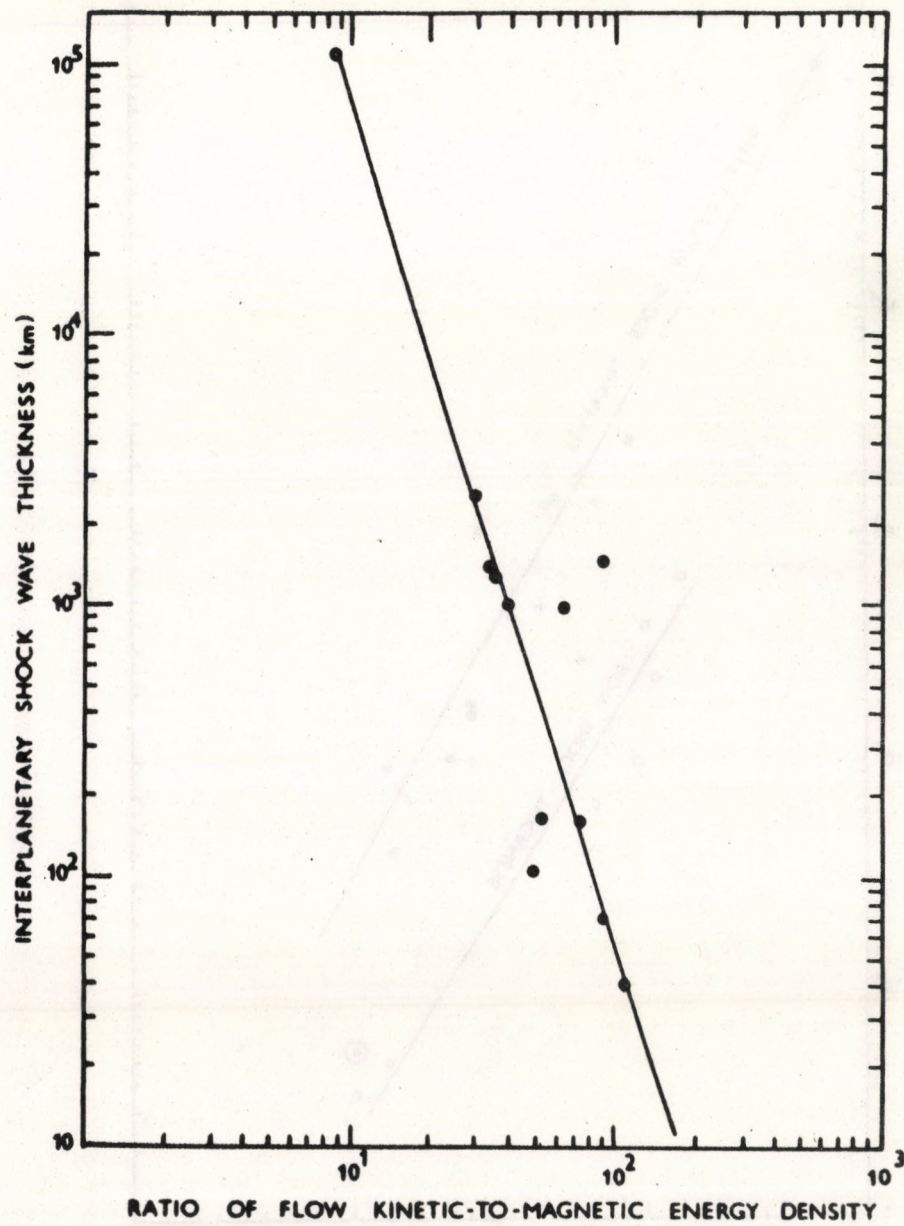
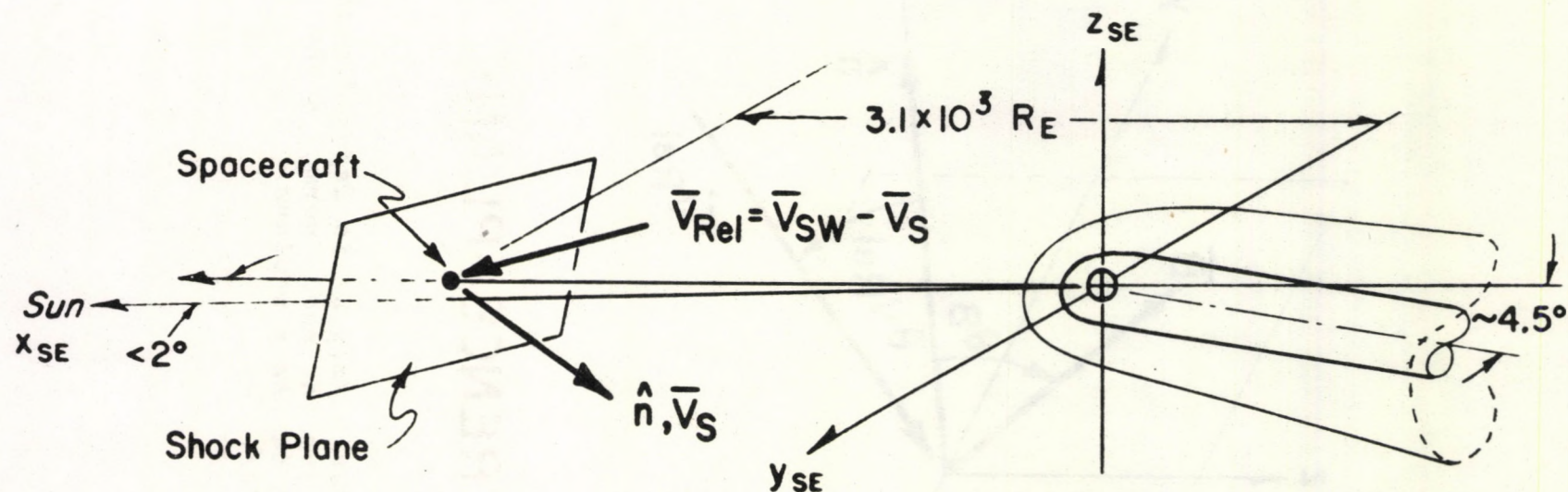
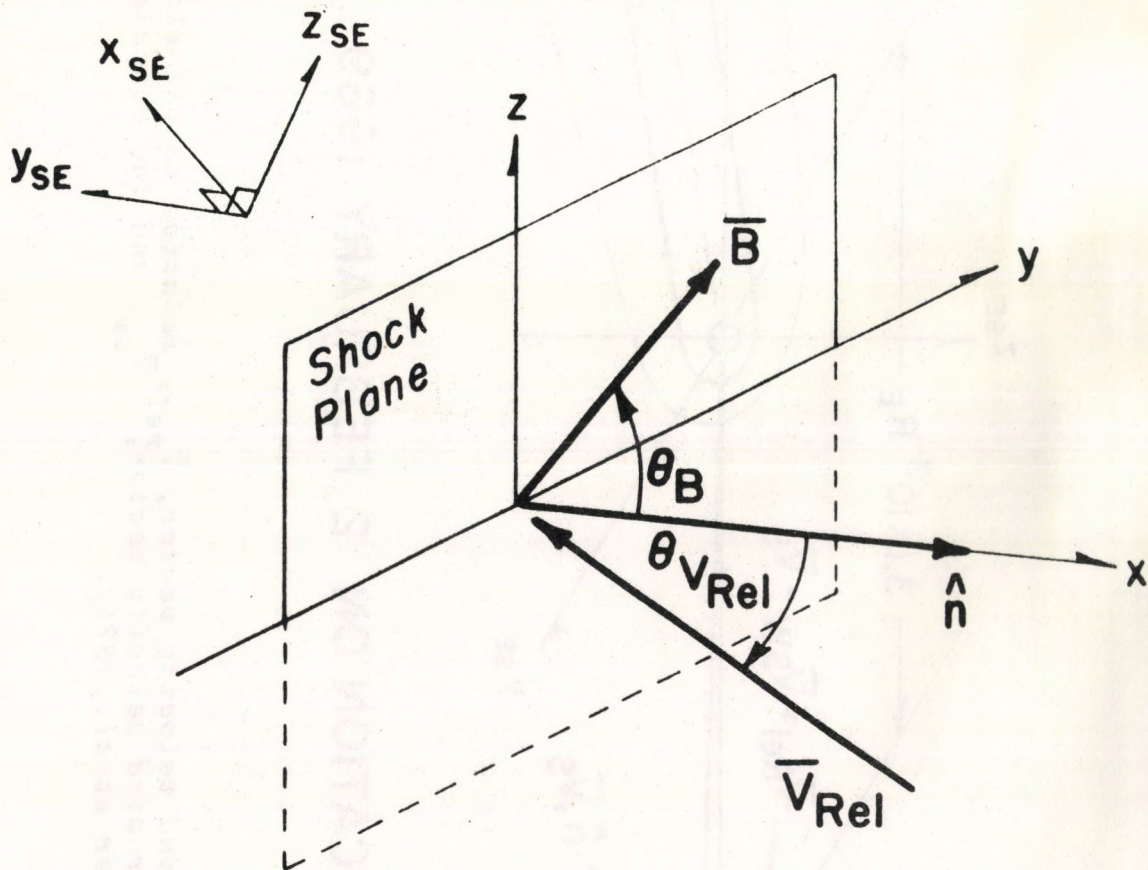


Fig.7. Shock thickness L_s versus α .



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Fig. 8. The definition of the solar wind velocity vector, \bar{V}_{rel} , relative to the shock plane in terms of the measured solar wind velocity vector, \bar{V}_{sw} , and the computed inertial shock velocity, \bar{V}_s /after Dryer et al., 1975/.



SHOCK REFERENCE PLANE

Fig.9. The shock coordinate system $/x,y,z/$ is defined such that the x axis lies along the shock normal n and the magnetic field lies in the x,z plane /after Dryer et al., 1975/.

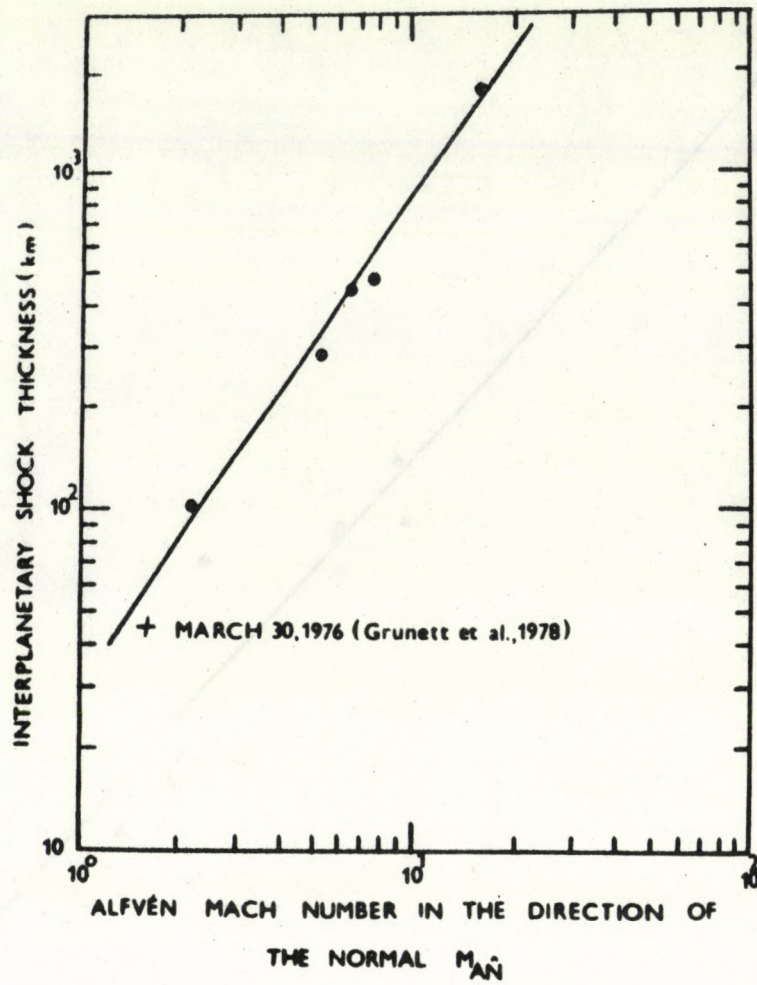


Fig.10. Shock thickness in various Mach number, $M_{A\hat{n}}$

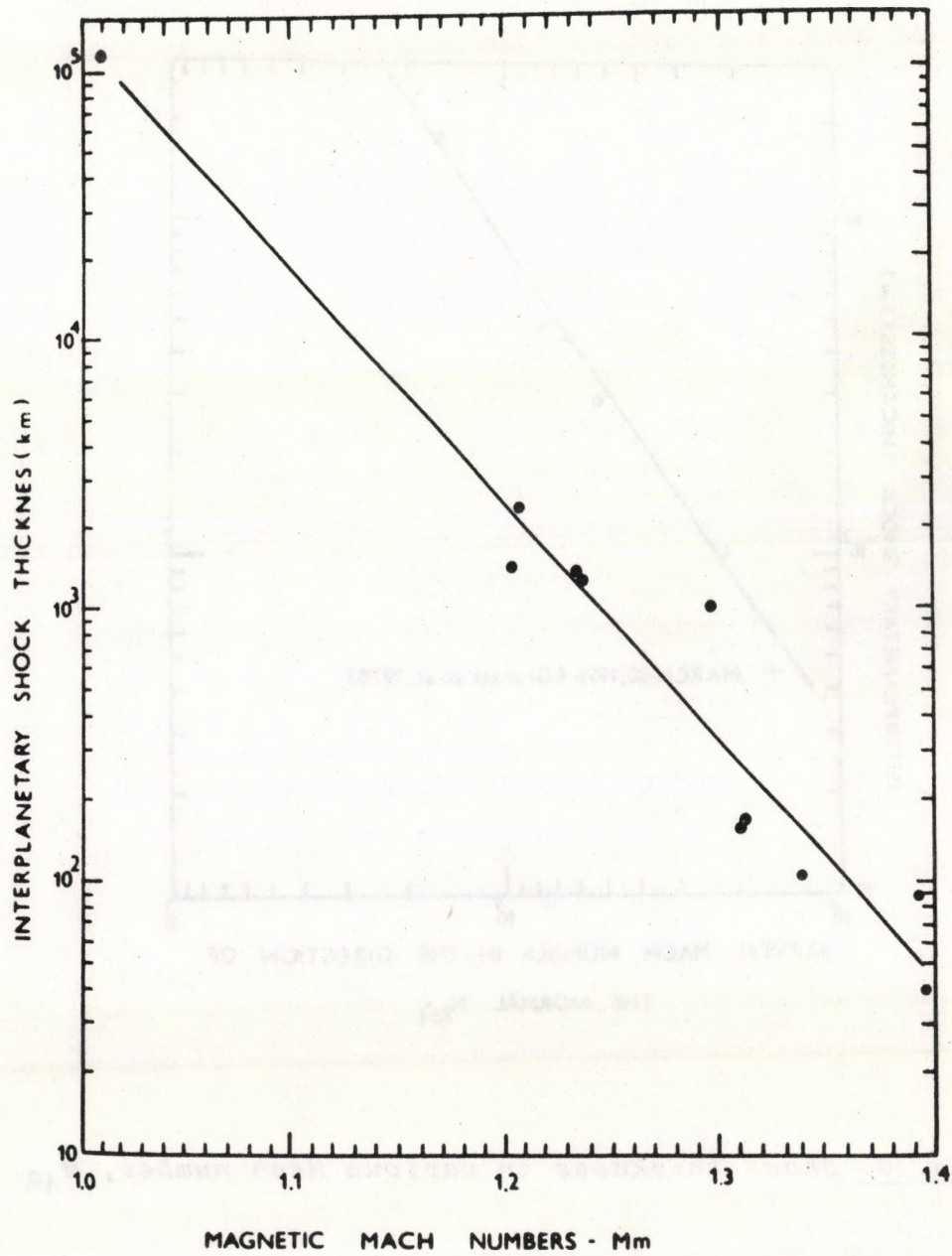


Fig.11. Shock thickness versus magnetic Mach number M_m .

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